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Comparative Growth Behavior of 3C-SiC Mesa Heterofilms With and Without Extended Defects

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Abstract. 3C-SiC was grown by step-free surface heteroepitaxy on 4H/6H-SiC on-axis wafers patterned with mesa structures. Under proper growth conditions, 3C-SiC films without stacking faults (SF's) or double positioning boundaries (DPB's) were achieved on many of the mesas. The growth rate of the 3C-SiC films with extended defects such as SF's and DPB's was considerably enhanced over SF/DPB-free 3C-SiC films. The experimental data, including atomic force microscope (AFM) studies of as-grown surfaces, indicate that defects act as preferred sites for nucleation of new 3C bilayers on the (111) growth surface. Larger growth rate discrepancies between mesas with and without SF defects are observed at higher 3C growth temperatures.

Introduction

Previous heteroepitaxial 3C-SiC crystal growth processes involved non-optimal nucleation on stepped surfaces of Si and SiC, resulting in high defect densities [1-3]. With the advent of "step free surface heteroepitaxy", growth of 3C-SiC on step-free 4H/6H-SiC mesas can produce 3C-SiC films that are completely free of SF's and DPB's [4-7]. The 3C-SiC polytype could overcome some of the inherent fundamental material properties that negatively affect 4H/6H-SiC device performance [5]. However, a better understanding of the 3C-SiC crystal growth process and defect structure is necessary in order to grow reproducible films for fundamental device studies. In this study of the growth of 3C-SiC on step free 4H/6H-SiC mesas, it has been observed that SF-free 3C-SiC films grow at substantially lower rates when compared to growth of 3C-SiC films with SF defects.

Experimental

Commercially available on-axis (within 0.3° of the basal plane) wafers of 4H/6H-SiC were patterned with an array of mesas [8]. The growth experiments were conducted in a horizontal-flow cold-wall chemical vapor deposition (CVD) reactor [9]. The carrier gas was H_2 with 3% SiH_4/H_2 and 5% C_3H_8/H_2 used as the growth precursors, and the growth pressure was 200 mbar. The mesa samples were exposed to an in-situ pregrowth etch (H_2 or HCl/H_2) to remove surface damage. Mesas that were free of screw dislocations (SD's) were rendered step free by carrying out homoepitaxial growth at temperature T_{SFG} as described more thoroughly in [5,10]. The temperature was then ramped down over a period of time, t_{ramp}, to the 3C-SiC nucleation temperature $T_{3C\text{-}nucleate}$ to intentionally nucleate 3C-SiC. After nucleation the temperature was set to T_{3CG} for a time period t_{3CG} until the end of the growth run [4-6]. Four separate samples were grown under the processes summarized in Table 1. Samples A and B were dry oxidized at 1150°C for eight hours to distinguish 3C epi films from 4H/6H epi films and to decorate SF's and DPB's [3]. Sample A was also etched in molten KOH to further decorate defects not decorated by oxidation [6]. AFM was used for observing as-grown (not oxidized) 3C-SiC film surfaces on samples C and D. Scanning electron microscopy (SEM) and optical microscopy were conducted to examine film thickness (mesa height) and defect content. Sample B, discussed further in [11], had an intentionally Al doped 3C-SiC heterofilm on a p-type 4H-SiC substrate that facilitated secondary ion mass spectrometry (SIMS) profiling of heteroepitaxial layer thickness. Sample C growth was kept short to enable AFM observation of near-heterointerface film morphology.

	3C-SiC Growth Parameters			
	Sample A	**Sample B**	**Sample C**	**Sample D**
Etch/t_{etch} (min)	H_2/5	H_2/5	H_2/5	HCl/10
T_{etch} (°C)	1630	1675	1675	1300
SiH_4 (sccm)	5.4	3.6	2.7	3.6
C_3H_8 (sccm)	9.0	4.5	4.5	3.0
Si/C	0.6	0.8	0.6	1.2
T_{SFG} (°C)	1630	1675	1675	1680
t_{ramp} (min)	15	10	1	10
$T_{3C\text{-}Nucleate}$ (°C)	1550	1535	1470	1500
T_{3CG} (°C)	1550	1675	1470	1700
t_{3CG} (min)	240	135	1	120

Table 1. Growth parameters for samples A-D.

Results

After 3C heteroepitaxial growth, optical microscopy of oxidized mesa films on samples A and B indicated that nearly all SD-free mesa films were 3C-SiC. For reasons discussed in [12], a few mesas with SD's remained entirely 4H-SiC. The height of 3C-SiC mesa films from samples A and B varied considerably even between adjacent mesas of the same initial size. 3C mesa films with SF defects were often observed to be substantially thicker than adjacent mesas without SF defects. For example, Fig. 1(a-b) compares adjacent mesas (#1 without and #2 with SF defect) from sample A (T_{3CG} ~ 1550 °C), while Fig. 1(c-d) shows a similar comparison of adjacent mesas with and without SF's on Sample B (T_{3CG} ~ 1675 °C). Significant crystal facets form on mesa edges for thicker 3C-SiC films (Fig. 1d mesa 2). Large 3C-SiC epilayer thickness variation was also observed when sample B was depth profiled by SIMS [11].

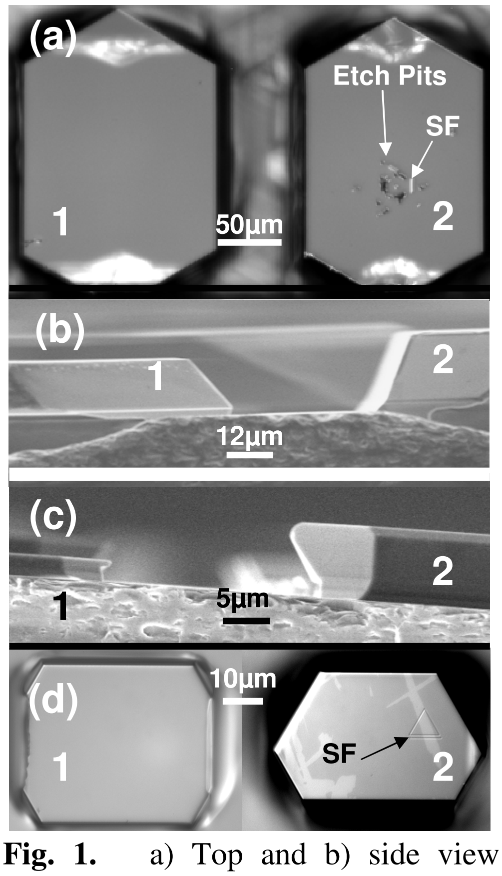

Fig. 1. a) Top and b) side view comparing defect content and height of two KOH-etched mesas from sample A. c) Side and d) top view comparing defect content and height of oxidized mesas from sample B.

The differences in mesa height among thirty groups of four adjacent 40 µm x 40 µm (pre-growth dimension) square mesas were studied as a function of mesa polytype and defect content on samples A and B. The results (normalized to a one-hour 3C growth time t_{3CG}) are plotted in Fig. 2. In most cases, SF-free 3C-SiC mesas were the shortest of each group, while 4H-SiC mesas with SD's exhibited the tallest mesa heights.

Fig. 3a shows an AFM image of the as grown surface of a 3C mesa from sample C (T_{3CG} ~ 1470°C, t_{3CG} = 1 min). All steps in the Fig. 3a image are the height of a single Si-C bilayer (0.25 nm). On the lower left side of the image, a pattern of tightly-spaced concentric steps is beginning to produce a triangular growth hillock on the surface of the very thin 3C heteroepilayer. Similar concentric step patterns at triangular hillock peaks in thicker 3C films have been observed, and KOH etching of these thicker films produced isolated etch pits at these peaks indicating the presence of a dislocation defect [4-6]. The majority of the sample C surface exhibited more random nucleation behavior similar to the upper right portion of Fig. 3a.

Fig. 3b shows an AFM image of the as-grown surface of a 3C mesa from sample D (T_{3CG} ~ 1700 °C). In particular, Fig. 3b shows the topmost terraces found on the entire hexagonally shaped mesa (60 µm on a side), as all growth steps across the rest of the mesa surface were observed to originate from (i.e., flow from) this area at the mesa edge. The straight line features (denoted SF-1 and SF-2 in Fig. 3b) are stacking faults [13]. The topmost terrace is bounded on one side by a stacking fault (SF-1) that intersects the mesa edge. Two additional mesas (out of three studied to date on sample D) also exhibited the property that all growth steps emanated from where stacking faults intersected the mesa edge. Some observed SF's did not generate growth steps.

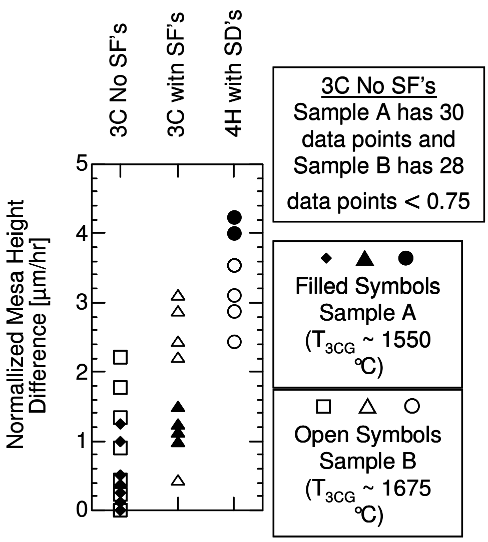

Fig. 2. Post-growth mesa height difference as a function of mesa structure and temperature (see text).

Discussion

As demonstrated in Figs. 1 and 2, the 3C-SiC heterofilm growth rate is generally larger with extended defects present. Also, the difference in thickness between 3C films with and without SF's is larger at higher temperature. Thus, the results of this study indicate that (1) the presence of defects (e.g., SF's) significantly accelerates the 3C growth rate relative to films free of extended defects, and (2) the magnitude of the growth rate difference increases with temperature.

The growth model for (111) oriented 3C-SiC within the temperature range of this study is one in which new Si-C bilayer islands are thermodynamically nucleated on top of existing (111) terraces on the growth surface, and these bilayer islands then kinetically expand laterally by step flow growth [5]. In contrast, 4H-SiC mesas with SD's grow thicker purely by kinetic mechanism, as the SD spiral continually supplies new bilayer steps needed for vertical mesa growth. Thus 4H-SiC mesas with screw dislocations exhibit the highest growth rate at both temperatures studied (Fig. 2). The difference in growth rate between 3C and 4H mesas therefore indicates that terrace nucleation, not stepflow, limits 3C growth rate in these experimental conditions. The terrace nucleation of new 3C bilayer islands can be either (1) somewhat "random" 2D terrace nucleation (not defect-assisted) of new bilayer islands, or (2) "defect-assisted" terrace nucleation of new bilayer islands at preferred surface sites related to defects or contamination.

The triangular growth hillock on the lower left side of Fig. 3a is consistent with defect-assisted nucleation, wherein accelerated nucleation at an isolated (non-screw) dislocation leads to the observed concentric (not spiral) pattern of closely-spaced steps forming the hillock. The upper right portion of Fig. 3a is more consistent with random terrace nucleation, wherein terraces and islands are larger with lower step density and less organization compared to the growth hillock. The additional bilayers and short step spacing of the Fig. 3a growth hillock clearly indicate accelerated bilayer nucleation at the defect, which with

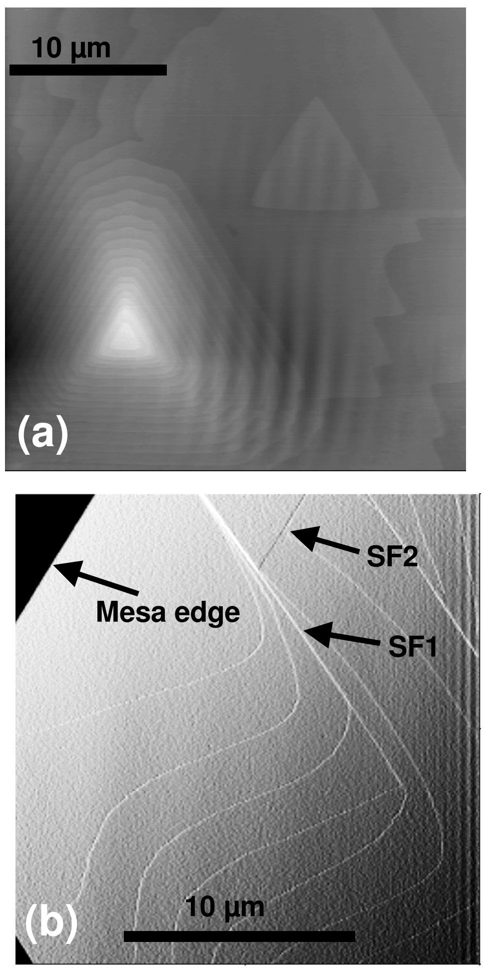

Fig. 3. AFM images of 3C mesas from (a) sample C (T_{3CG} ~ 1470 °C) and (b) sample D (T_{3CG} ~ 1700 °C). Single bilayer height (0.25 nm) steps are observed.

longer growth times dominates the morphology of thicker 3C-SiC mesa films. For 3C mesas without defects, additional bilayer growth proceeds, albeit somewhat more slowly, via the more random 2D terrace nucleation process.

At higher growth temperatures, the mobility of surface adatoms increases, causing the probability of random (111) terrace nucleation to decrease. This causes the growth rate on SF-free 3C-SiC mesas to decrease at high growth temperature (Fig 2). However, many 3C-SiC mesa films with SF defects grow nearly as fast (i.e., are nearly as tall) at high temperature as 4H-SiC mesas with SD's (Fig. 2). Preliminary measurements (Fig. 3b) point to the interaction of some stacking faults with some mesa edges as a dominant feature that rapidly supplies new bilayers to the high temperature 3C growth surface. We have also speculated that 3C mesa edge facets, which enlarge with crystal thickness, may play an important role in additional bilayer nucleation [13]. Better understanding of the interaction of various crystal edge facets, defects, and the top (111) 3C-SiC growth surface is necessary before a more complete model for high temperature 3C growth (with and without defect-assisted nucleation) is ascertained.

Conclusion

Growth of 3C-SiC by step free surface heteroepitaxy is accelerated in the presence of dislocations. At higher growth temperatures 2D nucleation is suppressed and growth is predominately step flow growth from defects or other as yet to be determined sources. At lower growth temperatures 2D terrace nucleation contributes to film growth.

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